Effect of Fiber Loading on Mechanical Properties, Friction and Wear Behaviour of Vinylester Composites under Dry and Water Lubricated Conditions

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***Abstract*-This paper explores the effect of fiber loading on mechanical properties, friction and sliding wear behaviour of vinylester composites under dry and water lubricated conditions under variation of normal applied loads and sliding speeds. Friction and wear experiments were carried out at ambient conditions on a Pin on disc machine arrangement. From the study it has been found that higher fiber content though improves some of the mechanical properties but also affect adversely some of the properties. The friction and wear properties of vinylester are improved by the addition of glass fiber as reinforced. The coefficient of friction increases with increase in applied normal load and sliding speed under dry sliding condition and decreases with increase in the applied normal load under water lubricated condition, but the specific wear rate for vinylester composites decreases with increase in applied normal load under both dry and water lubricated sliding conditions.**

***Keywords*-Vinylester composites; Mechanical properties; coefficient of friction; specific wear rate; SEM**

I. INTRODUCTION

Polymer composites have been increasingly applied as structural materials in the aerospace, automotive and chemical industries, providing lower weight alternatives to traditional metallic materials. A number of these applications are tribological components such as gears, cams, bearings and seals, where the self-lubrication of polymers is of special advantage. One of the features that make polymer composites so promising in industrial applications is the possibility of tailoring their properties with special fillers. Polymers and their composites are emerging as viable alternative material to metal based ones in many common and advanced engineering applications [1-3]. In the industries, the polymers and their composites are being increasingly used in view of their good strength and low densities. Besides, a wider choice of materials and ease of manufacturing make them ideal for engineering applications [4-6].

On account of their good combination of properties, fiber reinforced polymer composites are used particularly in automotive and aircraft industries, the manufacturing of space ship and sea vehicles [7-9]. Fiber reinforced polymer composites are the most rapidly growing class of materials due to their good combinations of high specific strength and specific modulus. Other important characteristics of these materials which make them more attractive compared to conventional metallic systems are low density and ability to be tailored to have stacking sequences that provide high strength and stiffness in directions of high loading [10-12].

Polymer composites consist of resin and a reinforcement two main constituents chosen according to the desired mechanical properties and the application for which they are to be employed [13]. Fibers are the principal constituents in a fibre-reinforced composite material. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure [14]. Among the fibre reinforcements glass, fibres are widely employed. Polymer composites reinforced with these fibres are usually one to four times stronger and stiffer than their unfilled matrices. It is also well established fact that no material is universally resistant to all modes of wear. Hence during material selection for typical tribo application it becomes imperative to know its complete spectrum of behavior in various possible wearing situations [15]. Glass fibre is also used for the bodies of specialty and sports cars. Glass fibres are electrical insulators, hence their considerable use in laminates for electrical insulation applications [16]. Glass fibers are produced also available in woven form. Varying density woven glass fabrics determine the mechanical properties of fabrics [17].

The role of polymer as a matrix in a fibre-reinforced composite is to transfer stresses between the fibres to provide a barrier against an adverse environment and to protect the surface of the fibres from mechanical abrasion. Glass fibre-reinforced polymer with thermoset polyester resin is an attractive material that is economically desired. Its application at low temperatures and under service terms is easy, when this material is compared to advanced polymer composites with complex molecule structure, high strength and working under terms of difficult service [19].

It is well known that the friction and wear behaviours of polymers in water lubricated condition differ generally from those in the dry sliding condition, and the absorption of water and plasticization of polymer surfaces influence the friction and wear of the polymer [20]. Also the absorption of water can lead to reduction in strength, modulus of elasticity, increase in the elongation and swelling of the surface layer [21, 22]. Lancaster [23] studied the lubrication of carbon fibre-reinforced polymers, and concluded that fluids such as water and other solutions inhibit the formation of transfer films of carbon/ polymer debris on the counter-face and the wear rates are greater than those obtained in dry conditions. In various study of polymer composites with water lubricated sliding conditions reduces the coefficient of friction but may increase the wear rate of the polymer composites [23, 24]. Tanaka et al. [24] investigated the wear behaviour of glass fiber, carbon fiber and carbon bead-reinforced polytetrafluoroethylene (PTFE). The glass-reinforced PTFE showed a very low wear rate with a steel counter face and finally concluded that the fiber preferentially supports the applied load and a fiber rich layer is produced during rubbing action on the mating surface. Unal and Mimaroglu [25] investigated the water lubricated tribological performance of carbon reinforced PEEK composite and they concluded that the coefficient of friction under water lubricated condition is lower than that the dry sliding condition, and he also found that friction and wear behaviour of PEEK composite also lead to a reduction of mechanical efficiency. Therefore the accurate knowledge of the influence of sliding speed and applied load value on the friction and wear is extremely important [26].

In recent years, much research has been devoted to exploring the potential advantage of thermoset matrix for composite applications [27]. One such matrix is vinylester, which has found a place in the family comprising the thermoset engineering polymers due to its excellent mechanical properties with good chemical corrosion resistance. It is also known that vinylester resins bond very well to fiber glass.

Also it is seen from the literature that, a very less amount of work is carried out on mechanical properties, friction and sliding wear behaviour of vinylester composites on a steel disc using a pin-on-disc arrangement under dry and water lubricated conditions. Thus the aim of the present work is to study the effect of fiber loading on mechanical properties, friction and sliding wear behaviour of vinylester composites under dry and water lubricated conditions.

II. EXPERIMENTAL DETAILS

A. Material and Panel Fabrication

In this investigation mechanical and sliding wear of 2D E-glass woven fiber in vinylester matrix composite has been studied. A combination of good mechanical, tribological properties and relatively lower cost of glass fiber makes them an attractive alternative for many engineering applications. The glass fiber chosen is most common type E-Glass fiber (density 2.54 gm/cm^3 and modulus72.4GPa) as reinforcing material in vinylester composites. The glass fabrics are woven in two perpendicular directions. The vinylester resin (density 1.23gm/cm^3 and modulus 2.4-4 MPa) is supplied by Northern Polymer Pvt. Ltd. New Delhi. Methyl ethyl ketone peroxide (MEKP), Cobalt Naphthenate is used as catalyst and accelerator respectively. The woven glass fabrics composites consist of fiber in three different quantities 40 wt%, 50wt% and 60 wt%.

For making of the samples wet hand layup technique is used. The layup procedure consisted of placing the glass sheet on the mould release sheet which has been sprayed by the mould release agent. On this a hardener, accelerator and vinylester resin mixed in required proportion is smeared. Over this, a layer of woven fabric sheet is laid down and resin prepared is spread once again. This procedure is repeated in all three cases unless the required thickness is obtained. A metal roller is used so that air bubbles could be removed and uniform thickness could obtain. After obtaining required thickness, it is covered once again at top by the mould release sheet, sprayed by release agent and smeared with layer of prepared resin. The whole assembly is placed in the mechanical press and pressure is applied and cured at room temperature for 24hours. The sheet prepared of sizes 300mm $\times$ 300mm of required thickness. The details of the composites including weight percentage are shown the Table 1. The test specimens used for tensile, compression, flexural, ILSS, Impact, Hardness and wear tests are cut according to ASTM standards from the respective sheets of fiber percentage 40wt%, 50wt% and 60wt% respectively by sample cutting saw.

B. Mechanical Properties

The Mechanical Properties such as tensile strength, compression strength, flexural strength and inter laminar shear strength (ILSS) were calculated by performing experiments on Hounsefield-25KN universal testing machines as per ASTM standard. The toughness tests were performed on plastic impact tester and hardness was determined on Rockwell hardness tester.

C. Wear Testing and Test Parameters

To evaluate the friction and sliding wear performance of vinylester and its composites of glass fiber reinforced prepared with varying fiber loading under dry sliding condition, wear tests were carried out in a pin-on-disc type friction and wear monitoring test rig (DUCOM) as per ASTM G 99. The counter body is a disc made of hardened ground steel (EN-32, hardness 72 HRC, surface roughness 0.7 μ Ra). The specimen is held stationary and the disc is rotated while a normal force is applied through a lever mechanism. During the test, friction force was measured by transducer mounted on the loading arm. The friction force readings are taken as the average of 100readings every 40seconds for the required period. For this purpose a microprocessor controlled data acquisition system is used.

A series of test are conducted with five sliding velocities of 1.6, 2.2, 2.8, 3.4 and 4m/s under five different normal loading of 10, 20, 30, 40 and 50N. For finding the specific wear, weight loss method was used. During these experiments initial and final weight of the specimens were measured. The material loss from the composite surface is measured using a precision electronic balance with accuracy $\pm$ 0.01 mg. The

specific wear rate (mm^3/N mm) is then expressed on 'volume loss' basis

$$K_s = \frac{\Delta M}{\rho L F_N} \quad (1)$$

Where

K_s- is the specific wear rate ($mm^3 N^{-1} mm^{-1}$)

ΔM- is the mass loss in the test duration (gm)

ρ- is the density of the composite (gm/cm^3)

F_N- is the average normal load (N).

III. RESULTS AND DISCUSSION

A. Density and Volume Fraction of Voids

The theoretical and measured densities along with the corresponding volume fraction of voids are presented in Table 1. It may be noted that the composite density values calculated theoretically from weight fractions which are not in agreement with the experimentally determined values. The difference is a measure of voids and pores present in the composites. It is clear from the Table 1 that increasing fibre content from 40wt% to 60 wt%, there is decrease in void fraction. GV_1 composite has the volume fraction of voids higher compared to other composite specimen GV_2 and GV_3. This may be due to the fact that GV_1 has 60% matrix material which may entrap air during the preparation of composite samples in hand layup technique.

The presence of voids or pores may be due to fibre interaction and fibre constraints on packing in composite laminates. This can affect composite performance adversely which may lead to swelling and reduction in density.

B. Hardness

The variation of composite hardness with the weight fraction of glass fibre is shown in Fig. 1. For the composite GV1, the hardness value is recorded as 84HRE while for GV2 as 85HRE and for composite GV3 is measured 87HRE. It is observed that with increase in the fibre content in the composite; improves the hardness, though the increment is marginal. It is well established fact that the strength properties of polymer composites are mainly obtained from the fibre contents and fibre strength. So the variation in the strength of composite with variation of fibre content is obvious.

C. Tensile and Flexural Strengths

These variations of composites GV1, GV2 and GV3 in tensile and flexural strengths are shown in Figure 2.

Gradual increase in both the tensile and flexural strength with fibre weight fraction is noticed. Similar observations have been already made for fibre reinforced thermoplastic composites. However it may be mentioned that both these strength properties of the composites are important for structural application.

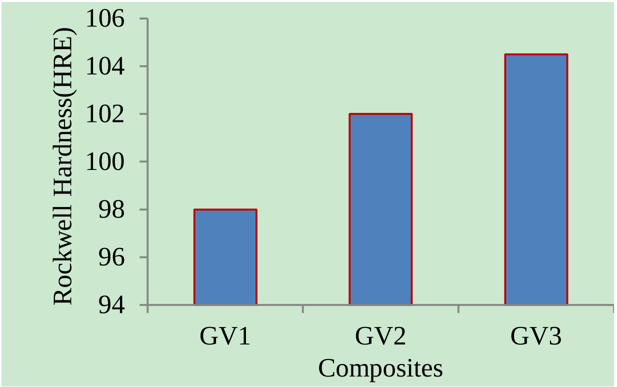


Fig.1 Variation of hardness for composites GV_1, GV_2 and GV_3

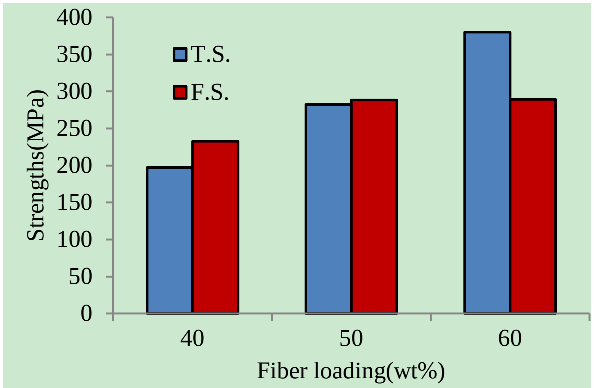


Fig.2 Variation of strengths for composites GV1, GV2 and GV3

TABLE I
MEASURED AND THEORETICAL DENSITY OF THE COMPOSITES (GV_1, GV_2 AND GV_3)

Materials	Composite Specification	Measured Density(gm/cc)	Theoretical density(gm/cc)	Volume fraction of voids (%)	Load (N)	Sliding speed(m/s)
GV_1	(Vinylester+40wt% glass fibre)	1.95	2.24	10.02	10 20 30 40 50	1.6 2.2 2.8 3.4 4.0
GV_2	(Vinylester+50wt% glass fibre)	2.25	2.36	4.58	10 20 30 40 50	1.6 2.2 2.8 3.4 4.0
GV_3	(Vinylester+60wt% glass fibre)	2.88	2.95	3.67	10 20 30 40 50	1.6 2.2 2.8 3.4 4.0

D. Inter Laminar Shear Strength (ILSS)

When a short beam is subjected to three points bending, the maximum shear stress (Interlaminar shear stress) occurs in the beam mid plane (neutral plane) where normal stresses are zero. This results in combination of failure modes, such as fibre rupture, micro buckling and interlaminar shear cracking. The maximum bending stresses (compression and tensile) occur at the beam upper and lower surfaces. The ratio (maximum shear stress / maximum bending stresses), increases as the beam span length to thickness ratio decreases, and thus the beam is more likely to fail in shear. An isotropic material in bending will fail in shear if (maximum shear stress / maximum bending stress), exceeds 0.58 according to the Von Mises criterion. Anisotropic materials may fail in shear at a lower (maximum shear stress / maximum bending stress) ratio. Since there is no guarantee that the specimen in a short beam shear test will fail in shear, the calculated value is referred to as the apparent interlaminar strength, which is a lower bound estimate to the interlaminar shear strength. Interlaminar shear strength depends primarily on the matrix properties and fibre matrix interfacial strength rather than fibre properties. ILSS can be improved by increasing the matrix tensile strength and matrix volume fraction. The glass fabric composite samples showed similar responses to those observed in three point bending. The failed specimen shows that the glass fibre sample did not reveal interlaminar failure. All these observations suggest that the glass fabric reinforced samples failed in bending in the SBS tests.

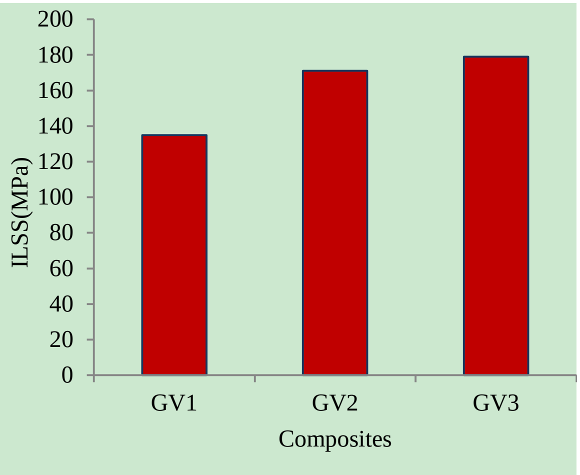


Fig. 3 Variation of ILSS strength for composites GV_1, GV_2 and GV_3

In the present work the ILSS values are measured for glass vinylester composites GV_1, GV_2 and GV_3 and an improvement is recorded in ILSS values with increase in the fibre content in them. Values are illustrated in the Figure 3.

E. Impact Strength

The study of impact behaviour of fibrous composite materials is an essential requirement before recommending for structural and engineering applications. The strength of matrix, fibre strength, orientation and weight fraction significantly influence the impact strength of the glass fibre vinylester composites. In the present investigation since the orientation is kept same in all three composite samples, the difference in the impact energy values will be due to the fibre content. The variation is shown in Figure 4.

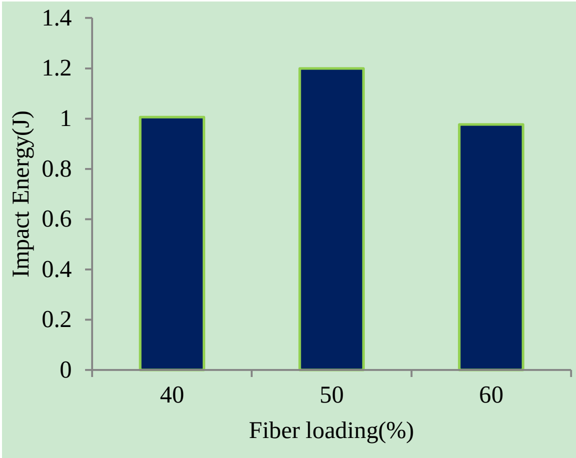


Fig. 4 Variation in impact energy for composites GV1, GV2 and GV3

A significant increase in impact strength is observed for increasing the fibre content from 40wt% to 50wt%. However with increasing the fibre content beyond this to 60wt%, there is decrease in the impact strength. Similar results have been reported in the earlier research. This fact can be considered a high content of fibres, poor dispersion and distribution of the fibres in the matrix. It seems that 50wt% of fibers is the limiting value to increase the impact properties of vinylester based composites. However at very high wt% of fibers, the role played by matrix to distribute the stresses developed is nullified and thus the failure becomes easier.

F. Wear Measurement

In this section friction and sliding wear characteristics of pure vinylester (V) and E-glass fibre vinylester composites GV_1, GV_2 and GV_3 under different applied normal loads and sliding speeds under dry sliding conditions are evaluated. Table 1 presents the physical properties and test conditions for the evaluation of coefficient of friction and specific wear rate of vinylester (V) and glass vinylester composites, GV_1, GV_2 and GV_3.

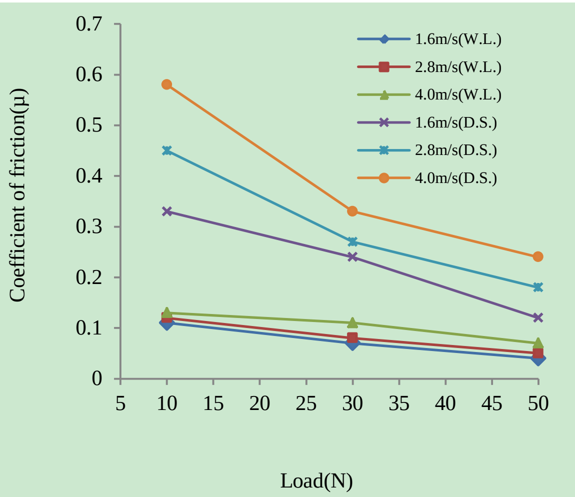
G. Effect of Normal Load and Sliding Speed on Coefficient of Friction

The experimental results for coefficient of friction for glass vinylester composites GV_1, GV_2 and GV_3 tested under normal loads of 10, 20, 30, 40 and 50N and sliding speeds of 1.6, 2.2, 2.8, 3.4 and 4m/s are shown in Figs. 5(a-c).

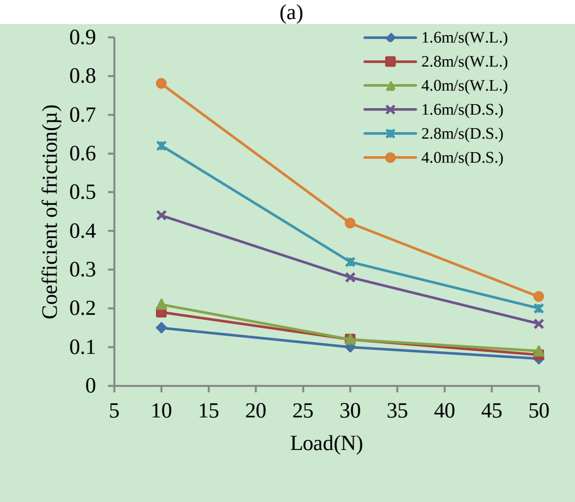
Figs 5(a-c) shows the variation in coefficient of friction with applied normal load under both dry and water lubricated sliding conditions.

From the Figs. 5(a-c) shows that the coefficient of friction increases with increase in applied normal load under dry sliding condition and decreases with increase in the applied normal load under water lubricated condition. Under all the test conditions the maximum coefficient of friction was found to be for vinylester composites GV_1 at sliding speed of 4 m/s and applied normal load of 50N under dry sliding condition,

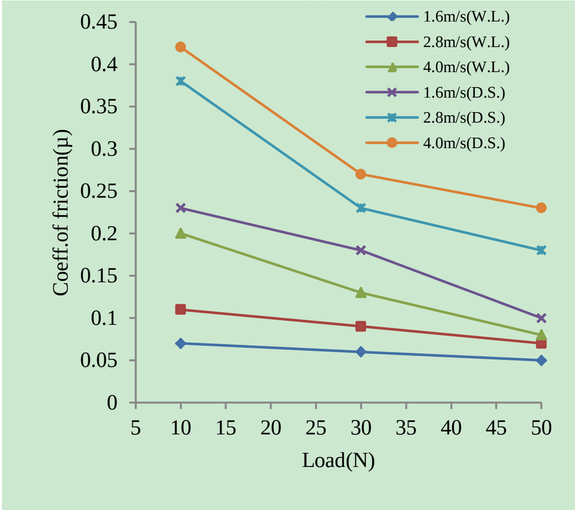
and minimum at sliding speed of 1.6 m/s and applied normal load of 50N under water lubricated dry sliding condition. Also from the Figs. 5 (a-c) it is observed that coefficient of friction increases with increase in sliding speed under both dry and water lubricated sliding conditions. The difference in coefficient of friction values between water lubricated and dry sliding conditions has an average of 56.55%. The mean overall difference is about 57%. But when the applied normal load increases to the limit load values of the polymer the friction will increase due to the critical surface energy. Further it can be explained as the frictional power increases the temperature of the steel surface, which leads to relaxation of polymer molecule chains and bond at fibre-matrix gets weakened. Due to which fibres are broken into fragments and form debris with matrix particles. Higher the glass fibre present in matrix more is the frictional resistance in dry sliding condition. Generally the coefficient of friction for vinylester and glass vinylester composites under water lubricated sliding conditions is lower than the dry sliding conditions. These reductions in coefficient of friction values are attributed to the part which water plays as lubricant. The presence of water at the interface of specimen and steel disc washes away the wear debris. This improves the thermal properties of specimen considerably and also this results into assisting of the occurrence of h ydrodynamic contact full film thickness.



(a)

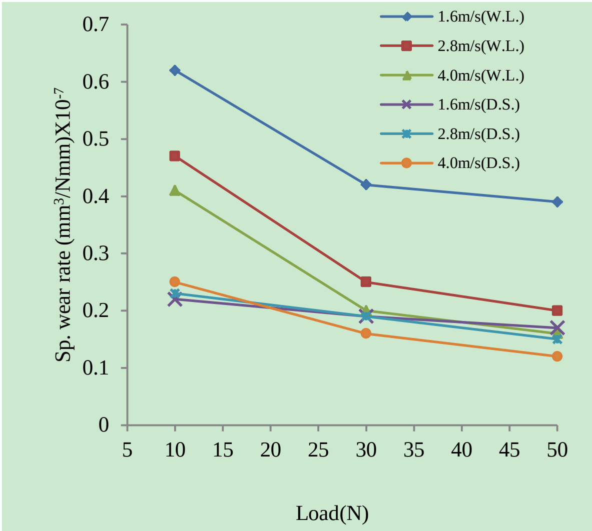


(b)

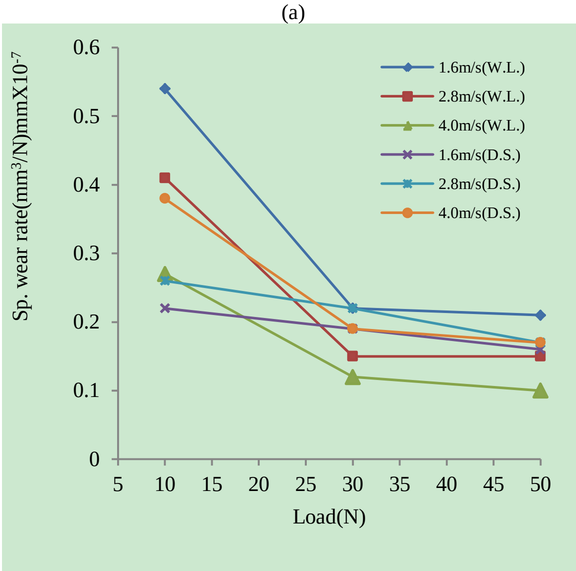


(c)

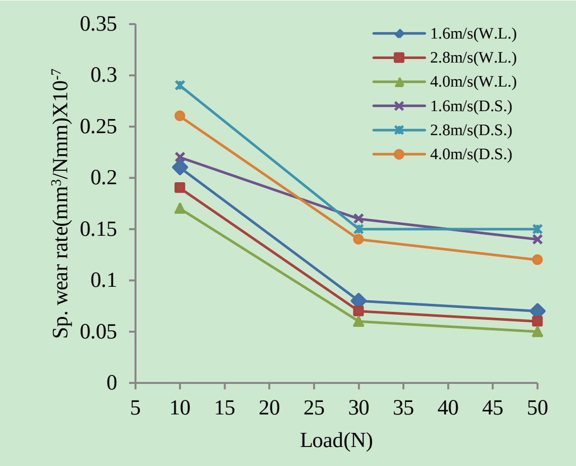
Figs. 5 (a-c) Variation of coefficient of friction with normal load under dry and water lubricated sliding conditions (a) GV_1 (b) GV_2 and (c) GV3



(a)



(b)



(c)

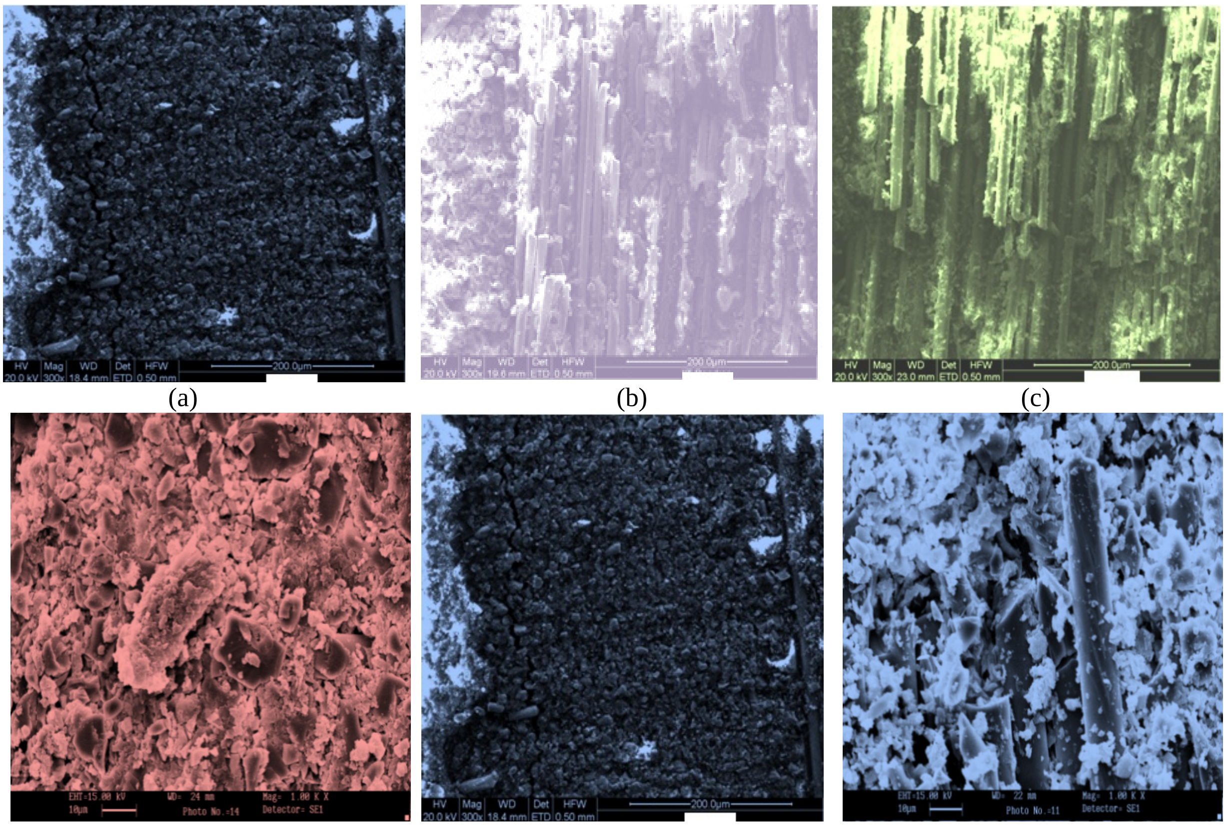
Figs. 6 (a-c) Variation in specific wear rate with applied normal load under dry and water lubricated conditions sliding condition (a) GV1 (b) GV2 (c) GV3

H. Effect of Applied Normal Load and Sliding Speeds on Specific Wear Rate

The specific wear rate values calculated from mass loss of E-glass fibre reinforced vinylester composites (GV_1, GV_2 and GV_3) tested under different testing conditions of load 10, 20, 30, 40 and 50N and speeds of 1.6, 2.2, 2.8, 3.4 and 4.0 m/s are shown in Figs. 6 (a-c).

The Figs. 6 (a-c) shows the variation of specific wear rate with applied normal load and sliding speeds under both dry and water lubricated sliding conditions. From Figs. 6 (a-c) it is evident from these figures that in this investigation within load range of 10N-50N, the specific wear rate is influenced by increasing the applied normal load and the sliding speeds. From the Figs. 6 (a-c) shows that the specific wear for vinylester composites decreases with increase in applied normal load under both dry and water lubricated sliding conditions. The Fig. 6 (a) shows that specific wear rate of glass vinylester composite GV_1 under water lubrication condition is higher than the dry sliding condition.

It is also noticed that under water lubrication sliding condition the specific wear rate decreases with increase in sliding speed. At lower sliding speeds there are differences in specific wear rates. From the Fig. 6 (b) it is observed that there is marginal difference in the specific wear rate for both under water lubricated and dry sliding conditions of composite GV_2. From the Fig. 6 (c) the observations show that the specific wear rate is lesser in water lubricated sliding condition than dry sliding condition of composite GV_3. It is also noticed that with increase in sliding speed the specific wear rate decreases. This is explained by the film layer formation on counter face in dry sliding conditions whereas in water lubrication this layer is removed and fresh composite surface is ready for sliding under water lubricated condition.



(a) (b) (c)

(d) (e) (f)

Figs. 7 SEM pictures of vinylester composites at 50N load and 4.0 m/s sliding speed under dry sliding (a) GV_1 (b) GV_2 (c) GV_3 and water lubricated conditions (d) GV_1 (e) GV_2 (f) GV_3.

Water prevents the formation of the transfer films of the fibre glass/vinylester matrix on the counterface by removing the debris [8].

The specific wear rate under water lubrication condition is close to those obtained in dry sliding conditions. More over the frictional heat loosens the bond between fibre and matrix due to thermal relaxation, which causes the loss of weight in dry sliding conditions. However in case of water lubricated conditions the effect of thermal penetration is avoided by cooling effect by the presence of water at interface of the composite specimen and steel disc. The fibre content also affects the wear behaviour of the glass vinylester composites. The composite GV_3 with 60wt% E-glass fibre reinforcement shows more compact bond and does not allow the polymer particles to wear out easily. Hence higher fibre content shows low wear loss particularly at higher sliding speeds.

I. Scanning Electron Microscopy

Typical SEM features of worn surfaces of E-glass vinylester composites GV_1, GV_2 and GV_3 at applied normal load of 50N and sliding speed of 4.0m/s are shown in figure 7. (a-f) under dry and water lubricated sliding conditions.

The surfaces of the specimens were examined directly by scanning electron microscope JEOL JSM-6480LV. The composite samples were mounted on stubs with silver paste. To enhance the conductivity of the samples, a thin film of platinum was vacuum-evaporated onto them before the photomicrographs are taken. The specific wear rate data in respect of selected samples is hereby discussed based on scanning electron microscopic features. Figure 7 (a) presents the features of worn surface of GV_1 composite specimen at applied normal load of 50N and sliding speed of 4.0m/s under dry sliding conditions.

From the surface the uniform distribution of matrix with small cracks, debris formation and very small amount of fibre exposure can be observed. SEM picture shown in figure 7 (d) presents the features of worn surface under water lubricated sliding conditions of composite GV_1 at applied normal load of 50N and sliding speed of 4.0m/s and it is observed that matrix is well spreaded and covering the fibres. This shows the smaller amount of wear in the presence of water as lubricant. Similarly the figures 7 (b) and 7 (e) present the SEM features of composite GV_2 under dry and water lubricated sliding conditions at applied normal load of 50N and sliding speed of 4.0m/s respectively. It is observed that under dry sliding condition fibre breakage, debris formation and fibre exposure depicting higher wear rate than under water lubricated conditions representing the fibre exposure with very small amount of matrix sticking to fibre only and effects of water acting as coolant and lubricant are seen. Figures 7 (c) and 7 (f) represent the worn surface features of composite specimens GV_3 under dry and water lubricated sliding conditions at applied normal load of 50N and sliding speed of 4.0m/s respectively.The observations of these surface show that wear of tested composite is lesser under water lubricated conditions. From this study it is noticed that increasing fibre contents in vinylester composites there is considerable reduction in specific wear rate. The effect of load is more pronounced on composite specimens than the sliding speeds.

IV. CONCLUSIONS

The following conclusions can be drawn from the present study:

- The density of the composite specimens is affected marginally by increasing the fiber content.

For the composites with higher percentagee of fiber content, cured at room temperature shows slight increase in density.

- Incorporation of higher percentage beyond 50% fiber loading to 60% has improved the tensile strength, tensile modulus and elongation. For 50% fiber reinforcement, composite laminates have maximum values for the flexural strength, ILSS strength but there is reduction in these properties when fiber content is increased further to 60%. The compression strength also reduced with increase in fiber content from 40% to 50% & 60% for the specimen.

- The coefficient of friction increases with increase in applied normal load and sliding speed under dry sliding condition and decreases with increase in the applied normal load under water lubricated condition, but the specific wear rate for vinylester composites decreases with increase in applied normal load under both dry and water lubricated sliding conditions.

- The response to friction and dry sliding wear in vinylester is influenced considerably

by the addition of woven bi-direction glass fiber as reinforcement and its amount also. The variation in the fiber content attempted in this work, exhibit lower wear loss compared to pure vinylester resin. This is due the reason that pure vinylester has small mechanical properties.

Therefore vinylester with fiber reinforcement improves load carrying capability that lower the wear rate. Also higher amount of glass fiber reinforcement reduces the specific wear rate.

- Wear study against Hardened grounded steel disc counterface under various loads and sliding speeds, the wear performances of vinylester and glass fiber reinforced composites with varying fiber loading are ranked as follow.

GV_3(Vinylester+60%GFR)>GV_2(Vinylester+50%GFR)>GV_1 (Vinylester+40%GFR) > V (Pure Vinylester) (K_S in the order of $10^{-8}mm^3N^{-1}m^{-1}$) and can be considered as a very good tribo material. The results are comparable to the epoxies and other tribo materials.

REFERENCES

[1] AS M Handbook, ASM international, Materials, Park, USA, 18,1992.

[2] L. Chang, Z. Zhang, C. Breidt, K. Friedrich, Tribological properties of epoxy nanocomposites: I. Enhancement of the wear resistance by nano-TiO2 particles, Wear 258 (2005) 141–148.

[3] L. Chang, Z. Zhang, Tribological properties of epoxy nanocomposites: II. A combinative effect of short fibre with nano-TiO2, Wear 260 (2006) 869–878.

[4] Kishore, P. Sampathkumaran, S. Seetharamu, A. Murali, R.K. Kumar,J. Reinforced Plastics and Composites 18 (1) (1999) 55–62.

[5] Kishore, P. Sampathkumaran, S. Seetharamu, S. Vynatheya, S.Murali, R.K. Kumar, SEM observations of the effects of velocity and load on the sliding wear characteristics of glass fabric–epoxy composites with different fillers, Wear 237 (2000) 20–27.

[6] A.A. Collyer, Rubber Toughened Engineering Materials, Chapman & Hall, London, 1994.

[7] H. Pıhtılı, N. Tosun, Investigation of the wear behaviour of a glass fibre-reinforced composite and plain polyester resin, Composite Sci. Technol. 62 (3) (2002) 367–370.

[8] N.S. El-Tayep, R.M. Gadelrap, Friction and wear properties of E-glass fiber reinforced epoksi composites under different sliding contact conditions, Wear 192 (1996) 112–117.

[9] M.T. Mathew et al. Tribological properties of the directionally oriented warp knit GFRP composites; Wear 263 (2007) 930–938.

[10] N. Chand, A. Naik, S. Neogi, Three-body abrasive wear of short glass fibre polyester composite, Wear 242 (2000) 38–46.

[11] I.M. Hutchings, Tribology; Friction and Wear of Engineering Materials, CRC Press, London, 1992, pp. 156–162.

[12] A.P. Harsha, U.S. Tewari, Polym. Test. 21 (2002) 697–709.

[13] M.R. Piggot, Load-Bearing Fibre Composite, Pergamon Press,Oxford, 1980.

[14] S.N. Kukureka, C.J. Hooke, M. Rao, P. Liao, Y.K. Chen, The effect of fibre-reinforcement on the friction and wear af polyamide 66 under dry rolling–sliding contact, Tribol. Int. 32 (1999) 107–116.

[15] Bijwe J, Indumathi J, John Rajesh J, Fahim M (2001) Wear 249:715

[16] P.K. Mallick, Fiber-Reinforced Composites: Materials, Manufacturing, and Design, Marcel Dekker, New York, 1988.

[17] L.N. Phillips, Design with Advanced Composite Materials, Springer, London, 1989.

[18] R. Ramesh, Kishore, R.M.V.G.K. Rao, Dry Sliding Wear Studies in Glass Fiber Reinforced Epoxy Composites, Wear 89 (1983) 131.

[19] P.B. Mody, T.W. Chou, K. Friedrich, J. Mater. Sci. 23 (1988) 4319–4330.

[20] M. Sumer, H. Unal, A. Mimaroglu., Evaluation of tribological behaviour of PEEK and glass fibre reinforced PEEK composite under dry sliding and water lubricated conditions. Wear 265 (2008) 1061–1065.

[21] M.D. Lutton, T.A. Stolarski, The effect of water lubrication on polymer wear under rolling contact condition, J. Appl. Polym. Sci. 54 (1994) 771–782.

[22] D.C. Evans, Polymer fluid interaction in relation to wear, in: Proceeding of the third Leeds-Lyon Symposium on Tribology, The wear of Non-Metallic Materials, Mechanical Engineering Publication Ltd., 1978, pp. 47–55.

[23] J.K. Lancaster, Lubrication of carbon fiber-reinforced polymers. Part 1. Water and aqueous solution, Wear 20 (1972) 315–333.

[24] K. Tanaka, Friction and wear of semi crystalline polymers sliding against steel underwater lubrication, Trans. ASME J. Lubric. Technol. 102 (4) (1980) 526–533.

[25] H. Unal, A. Mimaroglu, Friction and wear characteristics of PEEK and its composites underwater lubrication, J. Reinforced Plast. Compos. 16 (2006) 1659–1667.

[26] C.J. Hooke, S.N. Kukureka, P. Liao, M. Rao, Y.K. Chen, The friction and wear of polymers in non-conformal contacts, Wear 200 (1996) 83–94.

[27] B. Suresha, G. Chandramohan, Siddaramaiah, P. Sampathkumaran, S.Seetharamu, Mater. Sci. Eng. A 443 (2007) 285–291.